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(54) Title: IN FLIGHT DOPPLER WEATHER RADAR WIND SHEAR DETECTION SYSTEM
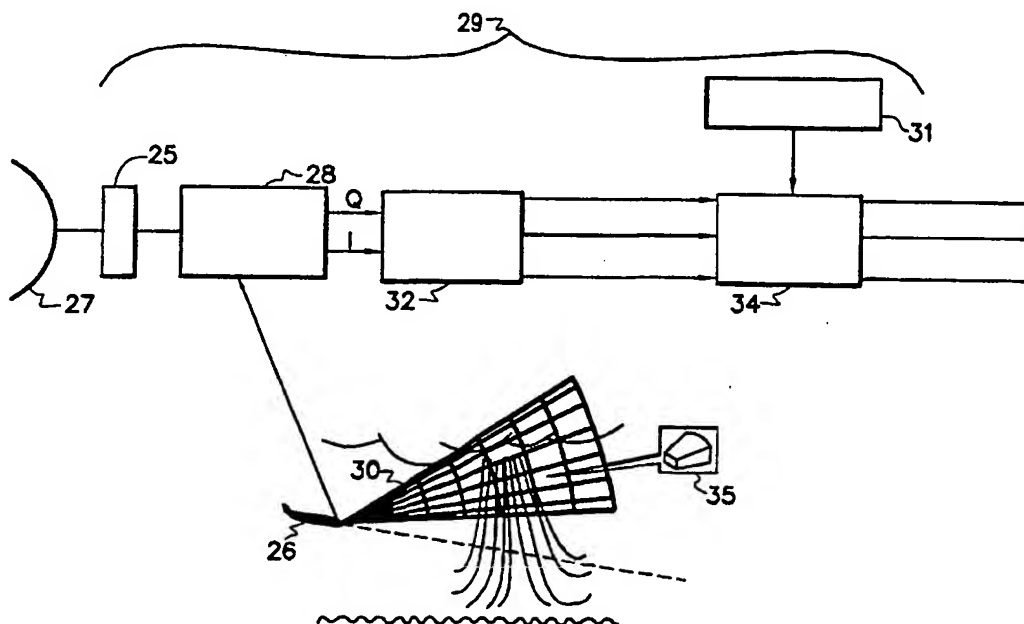
(57) Abstract

An airborne Doppler radar wind shear detection system has a volumetric scanning pattern for providing atmospheric measurement data for individual resolution cells that are formed into a 3-D grid of atmospheric data samples. Volumetric feature extraction modules identify and group resolution cells having particular features into air masses of interest. A spatial feature association and filtering module combines the air masses of interest into a 3-D representation of atmospheric conditions and filters out ground clutter. A contextual matching and temporal tracking module compares the 3-D representation to known wind shear models and compares successive 3-D representations to one another to aid in identifying hazardous wind shear conditions in the aircraft flight path.

IN FLIGHT DOPPLER WEATHER RADAR WIND SHEAR DETECTION SYSTEM

BACKGROUND OF THE INVENTION

The present invention relates generally to weather radar systems and particularly to airborne Doppler radar systems used to predict potentially dangerous wind shear conditions in the flight path of the aircraft.

Microburst wind shear is one of the most serious hazards of aviation, and is particularly dangerous to heavily loaded jet transports flying low and slow on final approach or on takeoff before a comfortable margin of airspeed has been established. Pilots and engineers have learned to expect and deal with the normal changes in horizontal winds as an aircraft descends. A microburst is different however and requires a very different response.

Typically a microburst is of very short duration and covers a small space geographically; the core of a microburst may be as small as 1 nautical mile or less in diameter. It appears suddenly, develops its dangerous potential and dissipates in a matter of minutes.

Early attempts to protect against this phenomenon included the development of a low-level wind shear alerting system. This alerting system consists of wind direction and velocity sensors around the perimeter of the airport, plus a central sensor. Data from the sensors are computed and displayed in the control tower and controllers then advise the pilots concerned. The information derived is seldom specific enough to justify aborting the takeoff or landing and the microbursts can sometimes pass undetected between the sensors or occur outside the sensor network.

Other efforts have resulted in wind shear warning systems aboard the aircraft. Presently systems are available which look at the inertial instrumentation and flight performance information aboard the aircraft and provide a warning when the accelerations experienced could be conducive to wind shear. These systems are called "reactive " systems because they detect hazardous flight conditions as the aircraft enters the wind shear condition.

The problem is that reactive wind shear detection may not provide the pilot with enough time to successfully escape the dang rous condition.

A serious problem faced by airborne radar wind shear warning systems that are viewing the airspace in the aircraft glide path is how to deal with ground clutter. When ground based radar wind shear warning systems are used the ground clutter problem may be dealt with more easily since the ground clutter is essentially stationary. For example, with ground based radar a ground clutter map may be made periodically and then subtracted from the radar information. However, with airborne radar the ground clutter is seen in the primary antenna beam and is constantly changing.

SUMMARY OF THE INVENTION

The present invention solves these and other needs by providing an airborne wind shear detection system that provides advance warning of a hazardous wind shear condition. In accordance with the present invention an airborne wind shear detection Doppler radar is provided which transmits successive beams into the airspace in front of an aircraft, receives reflected signals and analyzes the reflected signals for a hazardous wind shear condition. The radar utilizes a volumetric scan pattern which provides a three-dimensional (3-D) grid of atmospheric data samples, each characterized by a range, elevation and azimuth. Volumetric feature extraction processing identifies potential wind shear features within the 3-D grid. Spatial feature association processing groups data samples having the potential wind shear features into air masses of interest by grouping from upper elevation features downward. Filtering means removes noise and clutter from the air masses of interest and provides a 3-D representation of the air masses of interest. Contextual feature matching and temporal tracking module compares the current 3-D representation of air masses of interest to known 3-D wind shear models and to previous 3-D

representations of the same air masses of interest, and
provide an output signal when a hazard threshold is
xceeded.

5   BRIEF DESCRIPTION OF THE DRAWINGS
         Fig. 1 illustrates a vertical slice of microburst
winds and the microburst characteristics as seen from a
Doppler radar.
         Figs. 2a and 2b illustrate the functional stages of
10   the invention.
         Fig. 3 reveals additional details of Fig. 2.
         Figs. 4a, 4b and 4c are an artists rendering of a wet
microburst signature.
         Figs. 5a, 5b and 5c represent simulated input data for
15   a wet microburst case.
         Fig. 6a and 6b represent output data obtained with the
present invention from the simulated wet microburst input
data of Fig. 5a, 5b and 5c.
         Fig. 7a and 7b represent simulated input data for a
20   dry microburst case.
         Figs. 8a and 8b represent output data obtained with
the present invention from the simulated dry microburst
data of Fig. 7a and 7b.

25   DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT
         The characteristics of a microburst as seen from a
Doppler radar are described in Fig. 1. The left-hand side
of Fig. 1 shows the major characteristics of microburst
winds, and it can be seen that they are characterized by
30   converging winds and vertical winds in the upper portion of
the structure, rotation and slight divergence at mid-
structure, and diverging winds in the lower portion of the
structure. The overall diameter of a microburst is 4 km or
less. The Doppler velocities that will be observed by the
35   radar for convergence, rotation, and divergence are shown
at the right side of Fig. 1 as observed velocity
signatures.

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A Doppler radar/clutter/microburst simulation
capability for the volumetric scan approach has been
developed by modifying software and models provided in User
Guide for an Airborne Wind Shear Doppler Radar Simulation
(AWDRS) program, Report #DOT/FAA/DS-90/7, June 1990. This
simulation capability has provided us radar data samples
for testing the concepts in the invention. In addition, we
have developed our own software simulation of the wind
shear detection system described herein.

SIMULATION RESULTS

Using the Doppler radar microburst signature
simulation, sample data sets were generated to investigate
signature detectability versus range and power, 3-D
microburst signature characterization, and performance of
the volumetric microburst detection algorithms. The radar
transmit frequency for all of the data simulated was 9.3
GHz, and signatures from a wet microburst (maximum
reflectivity -60 dBZ) model and a dry microburst model
(maximum reflectivity -30 dBZ) were generated.

3-D MICROBURST SIGNATURE CHARACTERIZATION

Using a transmit power and range to microburst that
assured good signature quality, the signature
characteristics of a wet and dry microburst were
investigated. The results of this investigation show that
the velocity signatures of the microbursts are clearly
divergent for the lowest elevation scans (3 degrees above
the aircraft glide slope) and transform into a convergent
signature within the next 10 degrees of elevation. This
seems to be due to the turbulent "rolling" of the wind
outflow. The remainder of the upper scans (23, 33 and 43
degrees above glide slope) always exhibit the signature of
an approaching wind, sometimes accompanied by a receding
wind signature at a slightly closer range (indicative of
converging winds). The relatively strong approaching wind
signature is probably due to convergence of the microburst
winds amplified by the vertical wind component observable
by the Doppler radar with an elevated scan angle. In turn,
the receding wind signature will be attenuated by the

vertical microburst wind component at elevated scan angles. Rotation signatures were not observed in this investigation due to the axis-symmetric nature of the microburst models used. Presently available complete microburst model
5   renderings are under investigation to corroborate the robustness of observed rotational features in recognizing microburst wind shear. Fig. 4 shows an artist's rendering of a wet microburst signature at three elevation "slices." The actual Doppler color images could not be used here due
10 to publishing constraints. The dark colored areas are receding relative to the Doppler radar, and the light colored portions are approaching. Aircraft motion has been subtracted from the signatures.

The wind shear detection system of the present
15 invention utilizes a full 3-D volumetric scan pattern 30 as illustrated in Fig. 2 to interrogate the region ahead of aircraft 26 by means of signals emitted and received by antenna 27. Scanning radar transceiver 28 includes an antenna driver 25 and is preferably designed to scan
20 vertically in elevation and then step through the desired azimuth coverage as this scanning pattern seems most efficient for the detection of wind shear obstacles in front of aircraft 26. Scanning radar transceiver 28 provides both in-phase (I) and Quadrature (Q) data. Base
25 data processor 32 performs processing required in order to analyze the Doppler radar returns to determine the presence of wind shear. Three "base" data products of returned power, mean velocity and spectral width must first be calculated from the raw radar samples. There are several
30 known ways of calculating these products varying in complexity. The technique selected for the present invention was pulse pair processing, a technique that is relatively low in computational complexity and is widely used in pulsed Doppler weather radar signal processing.
35 Base data filter unit 34 corrects for receiver noise characteristics 31 and filters the returned power, mean velocity, spectral width data, antenna 27, scanning radar transceiver 28, base data processor 32, and base data

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filtering 34 functions are included in a conventional
airborne weather radar.

Volumetric scanning pattern 30 of the present
invention results in a grid of resolution cells 35 with
each cell having a unique range, elevation and azimuth.

Volumetric feature extraction function 40 requires
Divergence/Convergence module 50, Rotation module 60,
Reflectivity Core module 70 and Spectral Width Cluster
module 80.

After the three base products are calculated for each
cell in volumetric scan, individual characteristic features
of the microburst are searched for and spatially grouped
together. Once the individual signature features, i.e.,
divergence, convergence, rotation, high reflectivity, and
high spectral width are located, they are spatially
associated using the azimuthal-slice centroid of each
feature. This association forms a 3-D representation of
the radar observations, which can then be matched with the
known microburst characteristics as illustrated in Fig. 1.
The observed 3-D representations are tracked from scan to
scan and tested for consistency to provide robust
detection. The velocity signatures that are potentially
observable in a microburst are divergence, convergence, and
rotation as illustrated in Fig. 1. The potential shear
conditions that exist are along each radial scan, i.e.,
divergence or convergence or along each azimuth scan, i.e.,
clockwise or counterclockwise rotation. The grouping
algorithms operate on the differential velocity information
obtained by subtracting the mean velocity of each cell from
the previous cell. This subtraction is done along the
radial scan line for divergence and convergence and is done
across azimuth at a constant range for rotations. For a
Doppler radar base data processing approach that provides
differential radial velocities directly, the subtraction
step for computing the differential is only performed for
locating rotations. The beginning and the nd of a trend
group are identified by a consistent change of the
differential velocity sign. The change of the differential

velocity sign is along the radial for divergence and
convergence and along the azimuth for rotations. The
consistency of each sign change is tested with an operator
that eliminates spurious velocity differentials. The shear

5   value ($\Delta V/\Delta D$) and momentum ($\Delta V \times \Delta D$) of each trend group
are calculated and are used to eliminate identified trend
groups that are weak, i.e., low shear value and/or large
shear momentum. Once the initial trend groups are found,
they are grouped with other radial or azimuth trend groups

10 using a proximity operator. Thus the grouping process of
the present invention produces 3-D trend groups that
identify and spatially associate consistent divergence,
convergence, or rotations in the volumetric scan.

    The additional radar system hardware required to

15 implement the invention described herein is minimal. A
basic Doppler weather radar must already process the raw
radar data to determine reflectivity, velocity and spectral
width to generate standard displays of information. This
is the bulk of the required computational power of the

20 system, since typically many pulsed samples are averaged to
determine these quantities. The conventional airborne
weather radar functions are shown at 29. The additional
computational power required by this invention is minimal
compared to the determination of the basic Doppler radar

25 output data. It is envisioned that the algorithms be
hosted in an additional one or two digital signal
processing (DSP) chips within the airborne radar system
(based on typical Doppler weather radar system parameters
and scan rates, and state of the art DSP chip technology).

30 DSP chips functions and their associated memory are shown
at 94. This volumetric scan pattern should be easily
accommodated by most commercially available airborne
weather radar sets, since antennae are required to have
system controlled "tilt management". Tilt management

35 requires positioning motors to move the antenna in the
elevation direction. Modification to the standard control
mechanism to scan the antenna in an elevation - azimuth
step scan or similar pattern should be straightforward. A

more detailed description of the invention is provided in
the following.

In the more detail d descriptions that follow,
references are made to certain portions of the volumetric
5   scan pattern 30 employed by the radar to gather the grid of
resolution cells 35. Several terms are used repeatedly to
describe certain concepts; they are defined below.

Radial:

One-dimensional portion of resolution cell grid
10   covering all ranges for which radar data are measured at a
given azimuth and elevation antenna position. A radial
line segment is a portion of one complete radial.

Cross-Azimuth Arc:

One-dimensional portion of resolution cell grid
15   covering all azimuth angles for which radar data are
measured at a given range and antenna elevation angle. A
cross azimuth arc segment is a portion of one complete
cross azimuth arc.

Azimuth Slice:

20   Two-dimensional portion of resolution cell grid
covering all ranges and all elevation angles for which
radar data are measured at a given antenna azimuth angle.

Elevation Plane:

Two-dimensional portion of resolution cell grid
25   covering all ranges and all azimuth angles for which radar
data are measured at a given antenna elevation angle.

Air Mass:

The grouping algorithms operate to associate regions
of similar feature value that meet certain threshold
30   conditions. The resulting groups of the measured radar
data are referred to as "air masses" of interest, meaning a
region within the volumetric scan pattern that warrants
further feature/pattern processing to determine the hazard
to the aircraft. May also be referred to as "mass" or
35   "mass of interest".

Look:

A single complete volumetric scan may be referred to
as a "look" or "full scan look".

As features are extracted and grouped from the
measured radar data, the degree or extent that the
algorithms have performed grouping is referred to as "one-
dimensional," "two-dimensional" and "three-dimensional" or
5   "volumetric." Each grouping module ultimately results in
3-D or volumetric groups, meaning that feature association
have been determined for all azimuths, elevations and
ranges in the volumetric scan. Intermediate or partial
groupings are referred to as one-dimensional or two-
10   dimensional, depending on grouping process performed. For
example, groupings performed along a radial or cross-
azimuth arc are referred to as one-dimensional and
groupings performed across an azimuth slice or elevation
plane are referred to as two-dimensional.
15   Data From the Volumetric Scanning Pattern:
The basic input to modules 50, 60, 70 and 80 described
below is the output of the base data processor 32 and the
base data filtering 34 previously described (page 6). The
input for each module (50, 60, 70 or 80) will be either the
20   mean velocity, reflectivity or spectral width values from
modules 32 and 34. In addition, range, antenna position
relative to the airframe and airframe attitude shall
accompany each data sample to establish a mapping of data
samples from the volumetric scan pattern 30 to the physical
25   airspace ahead of the aircraft.
The current software implementation (described below)
of the invention concepts assumes that the radar
transceiver will scan through elevation before scanning
through azimuth (i.e., the sensor will scan vertically as
30   it steps through a horizontal scan). The concepts of
invention are straightforwardly adaptable to work with
different sequencing of the volumetric scan pattern.
Divergences/Convergences
Module 50 Output
35   Module 50 produces at 58 a list of volumetric (3-D)
air masses with similar wind velocity gradients along the
range distance dimension. These gradients represent
divergent and convergent air flows. The data associated

with each member (a single air mass of interest) of the
list includes:

- An internal identifier.
- The extreme positions of each of the six edges of
  the air mass as measured from the aircraft. That
  is, the range in azimuth, elevation, and range
  covered by the mass of interest.
- Minimum, Maximum, and Average Shear Value and
  Shear Momentum found within the air mass.
- A sublist of radial components of this air mass.
  For each radial line segment which makes up the
  volumetric air mass, we track the following
  information:
- Minimum and Maximum range of this radial segment.
- Change in air velocity over this segment.
- Shear Value of this segment.
- Shear Momentum of this segment.
- Hazard F-Factor for this segment.
- Elevation and Azimuth of this segment.

The hazard F-factor is described by R.L. Bowles in
"Wind shear Detection, Warning, and Flight Guidance," NASA
CP 10004: DOT/FAA/PS-87/2 October 1987. This factor
relates Doppler velocity measurements to aircraft dynamics
to form a quantified hazard factor of impending wind shear.

Module 50 Input

Module 50 has as input the mean velocity data samples
from the volumetric scanning pattern as previously
described.

Submodules 52, 54 and 56

Air masses of interest are found by going through
three major steps. First, for each radial of Doppler
velocities received (one velocity per each range bin in the
radial), we compute the differential velocities between
each range bin, then look for segments on the radial of
similar velocity differentials (i.e. regions of changing
velocity). Second, the segments found on each radial are
compared to segments found in similar positions on the
radial above it. Through these comparisons, we form a

collection of 2-D air masses with similar rates of changing velocity. This process is repeated for all radials in a single azimuth slice of the scan (i.e. a single scan through elevations). Third, the 2-D air masses of one

5   azimuth slice, are compared with the 2-D air masses of adjacent azimuth slices. These comparisons form the final collection of 3-D air masses which are the output of this module.

Find Radial Trends (1-D Grouping)

10   Submodule 52 Output

Submodule 52 creates a list of segments of interest on each radial. The information currently included for each segment in the list includes:

-    Minimum and Maximum range of this radial segment.

15   -   Change in air velocity over this segment.

-    Shear Value of this segment.

-    Shear Momentum of this segment.

-    Hazard F-Factor for this segment.

-    Elevation and Azimuth of this segment.

20   Submodule 52 Input

The unit of input to submodule 52 is a set of Doppler velocities along a single radar radial. There is one velocity value for each range bin along the radial. The differences between the velocities in adjacent range bins

25   are computed at the start of the submodule before looking for segments of interest along the radial.

The following operational parameters are also input to this submodule to fine tune its behavior:

-    Shear Value and Shear Momentum Threshold - Only

30   consider segments with shear and momentum values meeting a dual-parameter criterion based on a logical combination (i.e., and/or) of Shear and Shear Momentum Thresholds.

-    Bin Count Threshold - Only consider segments

35   containing at least this many Range Bins.

-    Test Count Threshold - M of N test criteria to help filter spurious data within a potential segment.

- Minimum Range - Only consider segments at or beyond this range distance.

Submodule 52 Process

Starting at the Far End of the radial, inward to the
Minimum Range:

- Find the start (far end) of a segment of interest
  (a change in velocity trend)
  This is done by looking for a change of sign in
  the velocity differentials while checking the
  values of each range bin from the Far End. An M
  of N check is performed to be sure that Range Bin
  suspected of being the start of a group is not
  just a noisy value compared to neighboring Range
  Bins.
- Find the end (near end) of a segment of interest.
- Compute Shear Value for this segment: (Delta
  Velocity/Delta Range Distance)
- Compute Shear Momentum for this segment: (Delta
  Velocity * Delta Range Distance)
- Add this segment to the list of 1-D segments of
  interest if each of the following thresholds is
  met: Bin Count Threshold, and logical
  combination of Shear Value Threshold and Shear
  Momentum Threshold.
- Look for the start of the next segment of
  interest.

Group Through Elevation (2-D Grouping)

Submodule 54 Output

Submodule 54 creates a list of 2-D air masses of
interest within a given azimuth slice. The data structure
of this 2-D air mass list is identical to the 3-D air mass
list described below as the output of the final submodule.
Each member of this list will contain information of each
set of radial segments that have been determined to belong
to the same 2-D feature in the air mass.

Submodule 54 Input

Submodule 54 takes as input the list created by the
Find Radial Trends (1-D Grouping) submodule described

above. This submodule will operate on a single azimuth slice of radials at once.

The following operational parameters are also input to submodule 54 to fine tune its behavior:

5   -   Adjacent Elevation Threshold - A segment of
             interest must be within a certain number of
             degrees in the elevation direction (the adjacent
             elevation threshold) of a segment on another
             radial in order to be logically considered part
10   of the same 2-D mass.

       -     Adjacent Range Threshold - Segments on separate
             radials within the Adjacent Elevation Threshold
             must also be within similar range distances from
             the sensor. Segments may be considered part of
15   the same mass if they are within this linear
             range distance of each other.

Submodule 54 Process

The highest elevation radial is the base for this grouping process.

20   Each segment of interest on this radial will become the top edge of a 2-D mass of interest.

Working downward from the second highest elevation radial to the lowest elevation radial:

For each radial:

25   -   For each 1-D segment of interest on this radial:
       -     Check the 1-D segments on the radials above this
             radial to find a higher segment which has the
             same characteristics (velocity differential
             trend) as this segment. Consider the Adjacent
30   Elevation Threshold and Adjacent Range Threshold
             to make this decision.

If a higher segment meeting the thresholds is found, then this segment is added to the 2-D mass of the higher segment, otherwise this segment will become the top edge of
35   a new 2-D mass of interest.

Group Across Azimuth (3-D Grouping)

Submodule 56 Output

Submodule 56 produces a list of volumetric (3-D) air masses with similar wind velocity gradients. The data associated with ach member (a single air mass of interest) of the list includes:

5   -   An internal identifier.

       -    The extreme positions of each of the six edges of the air mass as measured from the aircraft. That is, the range in azimuth, elevation, and range covered by the mass of interest.

10   -   Minimum, Maximum, and Average Shear Value and Shear Momentum found within the air mass.

       -    A sublist of radial components of this air mass. For each radial line segment (i.e. a portion of air mass between two range distances at a single

15   elevation angle and a single azimuth angle from the aircraft's radar sensor) which makes up the volumetric air mass, we track the following information:

       -    Minimum and Maximum range of this radial segment.

20   -   Change in air velocity over this segment.

       -    Shear Value of this segment.

       -    Shear Momentum of this segment.

       -    Hazard F-Factor for this segment.

       -    Elevation and Azimuth of this segment.

25   <u>Submodule 56 Input</u>

Submodule 56 takes as input the list created by the Group Through Elevation (2-D Grouping) submodule 54 described above. This submodule logically operates on a full scan "look" of data at once.

30   The following operational parameter is also input to submodule 56 to fine tune its behavior:

       -    Adjacent Azimuth Threshold - A 2-D mass of interest in a single azimuth slice must be within a certain number of degrees in the azimuth

35   direction (the adjacent azimuth threshold) of a 2-D mass of a nearby slice in order to be logically considered part of the same 3-D volumetric mass.

Submodule 56 Process

This algorithm uses either the right-most azimuth slice or the left-most azimuth slice as the base for the grouping process. This allows for bidirectional radar scans. Each 2-D mass of interest in the base azimuth slice will become the right/left edge of a 3-D air mass in the final output list of this module.

Working across from the second azimuth slice (next to the base azimuth slice) to the end azimuth slice at the opposite end of the scan:

For each azimuth slice:

- For each 2-D mass of interest in this azimuth slice:

- Determine a "bounding box" and "centroid" for this mass in this slice.

- Look through nearby (within Adjacent Azimuth Threshold) previous azimuth slices find a neighboring 2-D mass with the same characteristics (velocity differential trend) as this mass.

- If a previous segment meeting these requirements is found, then this mass is added to the 3-D mass of the previous segment, otherwise this mass will become the right/left edge of a new 3-D mass of interest.

Rotations

Module 60 Output

Module 60 produces at 68 a list of volumetric (3-D) air masses with similar wind velocity gradients along the cross-azimuth dimension. These gradients represent rotational airflows to the Doppler radar (since the radar senses radial velocities only). The data associated with each member (a single air mass of interest) of the list includes:

- An internal identifier.

- The extreme positions of each of the six edges of the air mass as measured from the aircraft. That

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is, the range in azimuth, elevation, and range
covered by the mass of interest.
- Minimum, Maximum, and Average Rotation Value and
Rotation Momentum found within the air mass.
5   - A sublist of cross-azimuth arc components of this
air mass. For each cross-azimuth arc segment
which makes up the volumetric air mass, we track
the following information:
- Left and Right Azimuth of this cross-azimuth arc
10   segment.
- Change in air velocity over this segment.
- Rotation Value of this segment.
- Rotation Momentum of this segment.
- Hazard Factor for this segment.
15   (The intent of the "Hazard Factor" for rotations
is to mimic the "F-Factor" used in
divergences/convergences (previously discussed)
for the case of the rotating wind field.)
- Range and Elevation of this segment.
20 <u>Module 60 Input</u>
Module 60 has as input the mean velocity data samples
from the volumetric scanning pattern as previously
described.
<u>Submodules 62, 64 and 66</u>
25   Air masses of interest are found by going through
three major steps. First, for each cross-azimuth arc in
the full scan, we compute the differential velocities
between adjacent range bins on the arc, then look for
segments of similar velocity differentials (i.e., cross-
30 azimuth regions of changing velocity). Second, the
segments found on each arc are compared to segments at
similar azimuth angles, at the same elevation angle, and at
nearby range distances from the sensor. Through these
comparisons we form a collection of 2-D air masses with
35 similar rates of changing velocity in the cross-azimuth
direction. This process is repeated for all cross-azimuth
arcs in a single elevation plane. Third, the 2-D air
masses of one elevation plane are compared with the 2-D air

masses on elevation planes above them. These comparisons form the final collection of 3-D air masses which are the output of this module.

Find Cross-Azimuth Trends (1-D Grouping)

5   ### Submodule 62 Output

Submodule 62 creates a list of segments of interest on each cross-azimuth arc. The information currently included for each segment in the list includes:

- Left and Right Azimuth of this cross-azimuth arc
10   segment.
- Change in air velocity over this segment.
- Rotation Value of this segment.
- Rotation Momentum of this segment.
- Hazard Factor for this segment.
15   - Range and Elevation of this segment.

Submodule 62 Input

Submodule 62 considers a single cross-azimuth arc as its basic unit of input. There is one velocity value for the range bin at each discrete azimuth angle along the arc.
20   The differences between the velocities in adjacent range bins are computed at the start of the submodule before looking for segments of interest along the arc.

The following operational parameters are also input to this submodule 62 to fine tune its behavior:

25   - Rotation Shear Value and Rotation Momentum Threshold - Only consider segments with rotation shear and rotation momentum values meeting a dual-parameter criterion based on a logical combination (i.e., and/or) of rotation shear and
30   rotation momentum thresholds.
- Azimuth Distance Threshold - Only consider segments with measured length greater than this linear distance threshold (measured between the two ends of the segment).
35   - Test Count Threshold - M of N test criteria to help filter spurious data within a potential segment.

- Minimum Range – Only consider arcs at or beyond this range distance.

Submodule 62 Process

Starting at one end of the arc, across to the opposite .

5   end:

- Find the start of a segment of interest (a change . in velocity trend)

  This is done by looking for a change of sign in . the velocity differentials while checking the

10   values of each sample across the arc. An M of N check is performed to be sure that the sample suspected of being the start of a group is not just a noisy value compared to neighboring samples.

15   - Find the end of a segment of interest.

- Compute Rotation Shear Value for this segment: (Delta Velocity/Delta Distance)

- Compute Rotation Momentum for this segment: (Delta Velocity * Delta Distance)

20   - Add this segment to the list of 1-D segments of interest if the following thresholds are met:

        Azimuth Distance Threshold, and a logical combination of the Rotation Shear Value Threshold and Rotation Momentum Threshold.

25   - Look for the start of the next segment of interest.

Group Through Range (2-D Grouping)

Submodule 64 Output

Submodule 64 creates a list of 2-D air masses of

30   interest within a given elevation plane. The data structure of this 2-D air mass list is identical to the 3-D air mass list described below as the output of final submodule 66. Each member of this list will contain information of each set of cross-azimuth arc segments that

35   have been determined to belong to the same 2-D feature in the air mass.

Submodule 64 Input

Submodule 64 takes as input the list created by the Find Cross-Azimuth Trends (1-D Grouping) submodule 62 described above. Submodule 64 will operate on a single elevation plane of radials at once.

5   The following operational parameters are also input to submodule 64 to fine tune its behavior:

- Adjacent Range Threshold - A segment of interest must be within this range distance of a segment on another radial in order to be logically
10   considered part of the same 2-D mass.

- Adjacent Azimuth Threshold - Segments on separate radials within the Adjacent Range Threshold must also be within similar azimuth distances from the sensor. Segments may be considered part of the
15   same mass if they are within this linear distance of each other.

Submodule 64 Process

The most distant (farthest range bin) cross-azimuth arc is the base for this grouping process.

20   Each segment of interest on this arc will become the far edge of a 2-D mass of interest.

Working inward from the second farthest range arc radial to the Minimum Range arc:

For each arc:

25   - For each 1-D segment of interest on this arc:
- Check the 1-D segments on the arcs beyond this arc to find a segment which has the same characteristics (velocity differential trend) as this segment. Consider the Adjacent Range
30   Threshold and Adjacent Azimuth Threshold to make this decision.

- If a more distant segment meeting the thresholds is found, then this segment is added to the 2-D mass of the further segment, otherwise this
35   segment will become the far edge of a new 2-D mass of interest.

Group Across Elevation (3-D Grouping)

Submodule 66 Output

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Submodule 66 produces a list of volumetric (3-D) air masses with similar wind velocity gradients (representing rotations). The data associated with each member (a single air mass of interest) of the list includes:

- An internal identifier.
- The extreme positions of each of the six edges of the air mass as measured from the aircraft. That is, the range in azimuth, elevation, and range covered by the mass of interest.
- Minimum, Maximum, and Average Rotation Value and Rotation Momentum found within the air mass.
- A sublist of cross-azimuth arc components of this air mass. For each cross-azimuth arc segment which makes up the volumetric air mass, we track the following information:
- Left and Right Azimuth of this cross-azimuth arc segment.
- Change in air velocity over this segment.
- Rotation Value of this segment.
- Rotation Momentum of this segment.
- Hazard Factor for this segment.
- Range and Elevation of this segment.

Submodule 66 Input

Submodule 66 takes as input the list created by the Group Through Range (2-D Grouping) submodule described above.

The following operational parameter is also input to submodule 66 to fine tune its behavior:

- Adjacent Elevation Threshold - A 2-D mass of interest in a single elevation plane must be within a certain number of degrees in the elevation direction (the adjacent elevation threshold) of a 2-D mass of an overhead plane in order to be logically considered part of the same 3-D volumetric mass.

Submodule 66 Process

This algorithm uses the highest elevation plane as the base for the grouping process. Each 2-D mass of interest

in the base elevation plane becomes the top edge of a 3-D air mass in the final output list of this module.

Working down from the second highest elevation plane (next to the top elevation plane) to the lowest elevation plane at the bottom of the scan:

For each elevation plane:

- For each 2-D mass of interest in this elevation plane:

- Determine a "bounding box" and "centroid" for this mass in this plane.

- Look through nearby (within Adjacent Elevation Threshold) higher elevation planes to find a neighboring 2-D mass with the same characteristics (velocity differential trend) as this mass.

- If a higher segment meeting these requirements is found, then this mass is added to the 3-D mass of the previous segment, otherwise this mass will become the top edge of a new 3-D mass of interest.

Reflectivity

Module 70 Output

Module 70 produces at 78 a list of volumetric (3-D) air masses with similar radar reflectivity values. The data associated with each member (a single air mass of interest) of the list includes:

- An internal identifier.

- The extreme positions of each of the six edges of the air mass as measured from the aircraft. That is, the range in azimuth, elevation, and range covered by the mass of interest.

- Minimum, Maximum, and Average Reflectivity found within the air mass.

- A sublist of radial components of this air mass. For each radial line segment which makes up the volumetric air mass, we track the following information:

- Minimum and Maximum range of this radial segment.

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- Minimum, Maximum, and Average Reflectivity of this segment.
- Elevation and Azimuth of this segment.

Module 70 Input

Module 70 has as input the radar reflectivity data samples from the volumetric scanning pattern as previously described.

Submodules 72, 74 and 76

Air masses of interest are found by going through three major steps. First, we look for segments on the radial of similar radar reflectivities. Second, the segments found on each radial are compared to segments found in similar positions on the radial above it. Through these comparisons, we form a collection of 2-D air masses with similar reflectivities. This process is repeated for all radials in a single azimuth slice of the scan (i.e. a single scan through elevations). Third, the 2-D air masses of one azimuth slice are compared with the 2-D air masses of adjacent azimuth slices. These comparisons form the final collection of 3-D air masses which are the output of this module.

Radial Range Bin Grouping (1-D Grouping)

Submodule 72 Output

Submodule 72 creates a list of segments of interest on each radial. The information currently included for each segment in the list includes:

- Minimum and Maximum range of this radial segment.
- Minimum, Maximum, and Average Reflectivity of this segment.
- Elevation and Azimuth of this segment.

Submodule 72 Input

The unit of input to submodule 72 is a set of radar reflectivities along a single radar radial. There is one reflectivity value for each range bin along the radial.

The following operational parameters are also input to submodule 72 to fine tune its behavior:

- Reflectivity Threshold - Only consider segments with a Reflectivity greater than this.

- Bin Count Threshold - Only consider segments
  containing at least this many Range Bins.
- Test Count Threshold - M of N test criteria to
  help filter spurious data within a potential
5   segment.
- Break Count Threshold - The number of Range Bins
  below the Reflectivity Threshold needed to
  determine a break between groups (hence, used to
  find the end of a group.)
10   - Minimum Range - Only consider segments at or
  beyond this range distance.

Submodule 72 Process

Starting at the Far End of the radial, inward to the
Minimum Range:
15   - Find the start (far end) of a segment of interest
  (a reflectivity over threshold)
  An M of N sliding window check is performed to be
  sure that a Range Bin suspected of being the
  start of a group is not just a noisy value
20   compared to neighboring Range Bins.
- Find the end (near end) of a segment of interest
  (use Break Count Threshold to confirm).
- Add this segment to the list of 1-D segments of
  interest if each of the following thresholds is
25   met: Bin Count Threshold, Reflectivity Threshold.
- Look for the start of the next segment of
  interest.

Group Through Elevation (2-D Grouping)

Submodule 74 Output

30   Submodule 74 creates a list of 2-D air masses of
interest within a given azimuth slice. The data structure
of this 2-D air mass list is identical to the 3-D air mass
list described below as the output of the final submodule.
Each member of this list will contain information of each
35   set of radial segments that have been determined to belong
to the same 2-D feature in the air mass.

Submodule 74 Input

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Submodule 74 takes as input the list created by the Radial Range Bin Grouping (1-D Grouping) submodule described above. This submodule will operate on a single azimuth slice of radials at once.

5   The following operational parameters are also input to this submodule to fine tune its behavior:

-      Adjacent Elevation Threshold - A segment of interest must be within a certain number of degrees in the elevation direction (adjacent
10   elevation threshold) of a segment on another radial in order to be logically considered part of the same 2-D mass.

-      Adjacent Range Threshold - Segments on separate radials within the Adjacent Elevation Threshold
15   must also be within similar range distances from the sensor. Segments may be considered part of the same mass if they are within this linear range distance of each other.

Submodule 74 Process

20   The highest elevation radial is the base for this grouping process.

Each segment of interest on this radial will become the top edge of a 2-D mass of interest.

Working downward from the second highest elevation
25   radial to the lowest elevation radial:
For each radial:

-      For each 1-D segment of interest on this radial:
-      Check the 1-D segments on the radials above this radial to find a higher segment which has similar
30   reflectivity characteristics as this segment. Consider the Adjacent Elevation Threshold and Adjacent Range Threshold to make this decision.

-      If a higher segment meeting the thresholds is found, then this segment is added to the 2-D mass
35   of the higher segment, otherwise this segment will become the top edge of a new 2-D mass of interest.

Group Across Azimuth (3-D Grouping)

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Submodule 76 Output

Submodule 76 produces a list of volumetric (3-D) air masses with similar reflectivity values. The data associated with each member (a single air mass of interest) of the list includes:

- An internal identifier.
- The extreme positions of each of the six edges of the air mass as measured from the aircraft. That is, the range in azimuth, elevation, and range covered by the mass of interest.
- Minimum, Maximum, and Average Reflectivity found within the air mass.
- A sublist of radial components of this air mass. For each radial line segment which makes up the volumetric air mass, we track the following information:
  - Minimum and Maximum range of this radial segment.
  - Minimum, Maximum, and Average Reflectivity of this segment.

  Elevation and Azimuth of this segment.

Submodule 76 Input

Submodule 76 takes as input the list created by the Group Through Elevation (2-D Grouping) submodule described above. Submodule 76 logically operates on a full scan "look" of data at once.

The following operational parameter is also input to submodule 76 to fine tune its behavior:

Adjacent Azimuth Threshold - A 2-D mass of interest in a single azimuth slice must be within a certain number of degrees in the azimuth direction (adjacent azimuth threshold) of a 2-D mass of a nearby slice in order to be logically considered part of the same 3-D volumetric mass.

Submodule 76 Process

This algorithm uses either the right-most azimuth slice or the left-most azimuth slice as the base for the grouping process. This allows for bidirectional radar scans. Each 2-D mass of interest in the base azimuth slice

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will become the right/left edge of a 3-D air mass in the
final output list of this module.

Working across from the second azimuth slice (next to
the base azimuth slice) to the end azimuth slice at the
opposite end of the scan:
For each radial:
- For each 2-D mass of interest in this azimuth
  slice:
- Determine a "bounding box" and "centroid" for
  this mass in this slice.
- Look through nearby (within Adjacent Azimuth
  Threshold) previous azimuth slices find a
  neighboring 2-D mass with the same reflectivity
  characteristics as this mass.
- If a previous segment meeting these requirements
  is found, then this mass is added to the 3-D mass
  of the previous segment, otherwise this mass will
  become the right/left edge of a new 3-D mass of
  interest.

Spectral Width

Module 80 Output

Module 80 produces at 88 a list of volumetric (3-D)
air masses with similar radar spectral width values. The
data associated with each member (a single air mass of
interest) of the list includes:
- An internal identifier.
- The extreme positions of each of the six edges of
  the air mass as measured from the aircraft. That
  is, the range in azimuth, elevation, and range
  covered by the mass of interest.
- Minimum, Maximum, and Average Spectral Width
  found within the air mass.
- A sublist of radial components of this air mass.
  For each radial line segment (i.e. a portion of
  air mass between two range distances at a single
  elevation angle and a single azimuth angle from
  the aircraft's radar sensor) which makes up the

volumetric air mass, we track the following
information:
-       Minimum and Maximum range of this radial segment.
-       Minimum, Maximum, and Average Spectral Width of
5   this segment.
-       Elevation and Azimuth of this segment.
        Module 80 Input
        Module 80 has as input the spectral width data samples
from the volumetric scanning pattern as previously
10   described.
        Submodules 82, 84 and 86
        Air masses of interest are found by going through
three major steps. First, we look for segments on the
radial of similar radar spectral widths. Second, the
15   segments found on each radial are compared to segments
found in similar positions on the radial above it. Through
these comparisons, we form a collection of 2-D air masses
with similar reflectivities. This process is repeated for
all radials in a single azimuth slice of the scan (i.e. a
20   single scan through elevations). Third, the 2-D air masses
of one azimuth slice are compared with the 2-D air masses
of adjacent azimuth slices. These comparisons form the
final collection of 3-D air masses which are the output of
this module.
25   Radial Range Bin Grouping (1-D Grouping)
        Submodule 82 Output
        Submodule 82 creates a list of segments of interest on
each radial. The information currently included for each
segment in the list includes:
30   -   Minimum and Maximum range of this radial segment.
        -       Minimum, Maximum, and Average Spectral Width of
                this segment.
-       Elevation and Azimuth of this segment.
        Submodule 82 Input
35   The unit of input to submodule 82 is a set of spectral
width values along a single radar radial. There is one
spectral width value for each range bin along the radial.

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The following operational parameters are also input to submodule 82 to fine tune its behavior:

- Spectral Width Threshold - Only consider segments with a Spectral Width greater than this.

- Bin Count Threshold - Only consider segments containing at least this many Range Bins.

- Test Count Threshold - M of N test criteria to help filter spurious data within a potential segment.

- Break Count Threshold - The number of Range Bins below the Spectral Width Threshold needed to determine a break between groups (hence, used to find the end of a group.)

- Minimum Range - Only consider segments at or beyond this range distance.

Submodule 82 Process

Starting at the Far End of the radial, inward to the Minimum Range:

- Find the start (far end) of a segment of interest (a spectral width over threshold) An M of N sliding window check is performed to be sure that a Range Bin suspected of being the start of a group is not just a noisy value compared to neighboring Range Bins.

- Find the end (near end) of a segment of interest (use Break Count Threshold to confirm).

- Add this segment to the list of 1-D segments of interest if each of the following thresholds is met: Bin Count Threshold, Spectral Width Threshold.

- Look for the start of the next segment of interest.

Group Through Elevation (2-D Grouping)

Submodule 84 Output

Submodule 84 creates a list of 2-D air masses of interest within a given azimuth slice. The structure of this 2-D air mass list is identical to the 3-D air mass list described below as the output of final submodule 86.

Each member of this list will contain information of each
set of radial segments that have been determined to belong
to the same 2-D feature in the air mass.

Submodule 84 Input

5   Submodule 84 takes as input the list created by Radial
Range Bin Grouping (1-D Grouping) submodule 82 described
above. Submodule 84 will operate on a single azimuth slice
of radials at once.

The following operational parameters are also input to
10   submodule 84 to fine tune its behavior:

- Adjacent Elevation Threshold - A segment of
  interest must be within a certain number of
  degrees in the elevation direction (adjacent
  elevation threshold) of a segment on another
15   radial in order to be logically considered part
  of the same 2-D mass.

- Adjacent Range Threshold - Segments on separate
  radials within the Adjacent Elevation Threshold
  must also be within similar range distances from
20   the sensor. Segments may be considered part of
  the same mass if they are within this linear
  range distance of each other.

Submodule 84 Process

The highest elevation radial is the base for this
25   grouping process.

Each segment of interest on this radial will become
the top edge of a 2-dimension mass of interest.

Working downward from the second highest elevation
radial to the lowest elevation radial:

30   For each radial:

- For each 1-D segment of interest on this radial:
- Check the 1-D segments on the radials above this
  radial to find a higher segment which has the
  same spectral width characteristics as this
35   segment. Consider the Adjacent Elevation
  Threshold and Adjacent Range Threshold to make
  this decision.

        -    If a higher segment meeting the thresholds is
             found, then this segment is added to the 2-
             dimension mass of the higher segment, otherwise
             this segment will become the top edge of a new 2-
 5   D mass of interest.
        Group Across Azimuth (3-D Grouping)
        Submodule 86 Output
        Submodule 86 produces a list of volumetric (3-D) air
masses with similar spectral width values. The data
10 associated with each member (a single air mass of interest)
of the list includes:
        -    An internal identifier.
        -    The extreme positions of each of the six edges of
             the air mass as measured from the aircraft. That
15   is, the range in azimuth, elevation, and range
             covered by the mass of interest.
        -    Minimum, Maximum, and Average Spectral Width
             found within the air mass.
        -    A sublist of radial components of this air mass.
20   For each radial line segment (i.e. a portion of
             air mass between two range distances at a single
             elevation angle and a single azimuth angle from
             the aircraft's radar sensor) which makes up the
             volumetric air mass, we track the following
25   information:
        -    Minimum and Maximum range of this radial segment.
        -    Minimum, Maximum, and Average Spectral Width of
             this segment.
        -    Elevation and Azimuth of this segment.
30   Submodule 86 Input
        Submodule 86 takes as input the list created by the
Group Through Elevation (2-D Grouping) submodule described
above. Submodule 86 logically operates on a full scan
"look" of data at once.
35   The following operational parameter is also input to
submodul 86 to fine tune its behavior:
        Adjacent Azimuth Threshold - A 2-D mass of interest in
a single azimuth slice must be within a certain number of

degrees in the azimuth direction (adjacent azimuth
threshold) of a 2-D mass of a nearby slice in order to be
logically considered part of the same 3-D volumetric mass.

Submodule 86 Process

This algorithm uses either the right-most azimuth
slice or the left-most azimuth slice as the base for the
grouping process. This allows for bidirectional radar
scans. Each 2-D mass of interest in the base azimuth slice
will become the right/left edge of a 3-D air mass in the
final output list of this module.

Working across from the second azimuth slice (next to
the base azimuth slice) to the end azimuth slice at the
opposite end of the scan:

For each radial:

- For each 2-D mass of interest in this azimuth
  slice:
- Determine a "bounding box" and "centroid" for
  this mass in this slice
- Look through nearby (within Adjacent Azimuth
  Threshold) previous azimuth slices find a
  neighboring 2-D mass with the same spectral width
  characteristics as this mass.
- If a previous segment meeting these requirements
  is found, then this mass is added to the 3-D mass
  of the previous segment, otherwise this mass will
  become the right/left edge of a new 3-D mass of
  interest.

3-D Spatial Feature Association and Filtering Module 90

The purpose of module 90 is to combine the data
outputs (for a single full scan look) of the previous four
data grouping modules: Divergences/Convergences 50,
Rotations 60, Reflectivity 70, and Spectral Width 80.
Filtering criteria are also applied to the 3-D grouped air
masses to remove the noise and clutter influences from the
contents of the resultant 3-D air masses of interest list.

Module 90 Output

Module 90 outputs a list of 3-D air masses of interest
which combines the data of the input lists, and filters out

the air masses which do not contribute to (or even distract
from) the detection of microbursts and wind shear events.

Module 90 produces at 92 3-D observation
representations or a list of volumetric (3-D) air masses
with similar characteristics which may indicate the
presence of a microburst or wind shear threat. The data
associated with each member (a single air mass of interest)
of the list includes:

- An internal identifier.
- The extreme positions of each of the six edges of
  the air mass as measured from the aircraft. That
  is, the range in azimuth, elevation, and range
  covered by the mass of interest.
- Minimum, Maximum, and Average Shear Value and
  Shear Momentum found within the air mass.
- Minimum, Maximum, and Average Rotation Shear
  Value and Rotation Momentum within the air mass.
- Minimum, Maximum, and Average Reflectivity and
  Spectral Width Values within the air mass.
- A sublist of radial components of this air mass.
  For each radial line segment (i.e. a portion of
  air mass between two range distances at a single
  elevation angle and a single azimuth angle from
  the aircraft's radar sensor) which makes up the
  volumetric air mass, we track the following
  information:
  - Minimum and Maximum range of this radial segment.
  - Change in air velocity over this segment.
  - Shear Value of this segment.
  - Shear Momentum of this segment.
  - Hazard Factor for this segment.
  - Minimum, Maximum, and Average Reflectivity for
    this segment.
  - Minimum, Maximum, and Average Rotation Shear
    Value and Rotation Momentum for this s gment.
  - Minimum, Maximum, and Average Spectral Width for
    this segment.
  - Elevation and Azimuth of this segment.

Module 90 Input

The major input to module 90 are the output lists of these modules:

- Divergence/Convergence module 50
5 - Reflectivity module 70
- Spectral Width module 80
- Rotations module 60

See these modules' descriptions contained herein for details of the data in these lists.

10   In addition, known 3-D microburst characteristics in the form of stored data models are input for aiding in the filtering process.

The following operational parameters are also input to module 90 to fine tune its performance:

15   -   Minimum Group Area - 3-D masses on a single elevation must be larger than this minimum area to be considered as a possible wind shear or microburst threat. (This helps eliminate ground clutter and noise. This parameter is determined

20   by typical microburst size and the desired sensitivity of the warning system.)

Module 90 Process

The approach of the algorithm is:

- Establish knowledge of potential ground clutter
25   regions within the grid of resolution cells (35) from the volumetric scanning pattern (30). Parameters from the volumetric scan pattern (azimuth, elevation and range sampling intervals) are used to establish this knowledge along with

30   information relating to the antenna position to the airframe, airframe attitude, and antenna beam width. A "flat earth" model is used to determine intersection points of the resolution cell grid with the earth's surface.

35   -   Strip out 3-D masses within the Divergences/Convergences list which are composed of segments on only a single radial. (These will

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usually be the result of ground clutter or
noise.)

- Strip out 3-D masses within the
Divergences/Convergences list which exist only on
a single elevation plane (usually ground clutter)
that have a surface area smaller than Minimum
Group Area.
- Strip out 3-D masses within the
Divergences/Convergences list that are located in
potential ground clutter regions (from knowledge
established as described above) and have no
corroborating evidence in elevations where ground
clutter is known not to be present.
- Merge Reflectivity values and Spectral Width
values from corresponding 3-D air masses in the
other input lists into the stripped list to
create the output list of 3-D air masses of
interest.

Contextual Feature Matching and Temporal Tracking

Module 100 has two principle functions. One, to track
features output by the 3-D spatial feature association and
filtering module over the course of multiple "looks".
Hence the development of significant features of interest
will be tracked as time progresses. This will allow us to
spot the development of microbursts and give the ability to
predict where a wind shear may exist within the next few
minutes. (The leading edge of a microburst will descend
from high altitudes toward the ground. Our data tracking
allows us to spot this.) Significant features are tracked
relative to the aircraft as the aircraft moves through
previously scanned areas. Changes in the radar's
perspective are compensated for on significant features to
aid tracking of those features.

The second function is to compare data configurations
of significant features with stored data models of
contextual features known to exist with microbursts and
wind shear conditions. Computer memory 101 is provided to
store model date. The spatial relationship between

diverging, converging and rotating wind fields as well as high spectral width and high radar reflectivity regions comprises the basic microburst model. In addition, knowledge of the time history evolution of the model is

5   incorporated in the algorithm. The model-feature comparison operation draws upon techniques recently and currently being developed in the computer science subfields of Knowledge Engineering, Machine Learning, and Contextual. Pattern Matching.

10   Module 100 Output

The ultimate output of module 100 is a set of alerts and warnings to the pilot and flight deck crew of the aircraft. The minimum warning time is fifteen to thirty seconds before the aircraft may pass through a wind shear

15   or microburst event. The form of the alert will be both audible and visual alerts and a radar screen display showing the position of hazard events relative to the aircraft and its course.

Module 100 Input

20   The lists of 3-D air masses of interest from the 3-D Spatial Feature Association and Filtering module will be collected for each "look" or full radar scan. Multiple "looks" will be used for Temporal Tracking.

The algorithm will also have stored data models of

25   known wind shear contextual features to assist in confirming microburst and wind shear conditions.

Module 100 Process

The lists of 3-D air masses of interest along with the volumetric scan pattern sampling interval descriptions,

30   relationship of antenna position to the airframe, and ancillary airframe attitude, position and motion information form the "world observation model" of the wind shear measurement system. This world observation model is the clearinghouse for all current information regarding

35   system observations. It also serves as the event "tracking file", keeping track of air mass of interest motion relative to the airframe and changes in features observed within each air mass of interest.

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Based on the data contained in the world observation
model described above and the stored a priori 3-D
microburst data models (previously described), module 100
performs the following functions:

5   -   Match to contextual models:
              The data in the world observation model are
              matched to known "a priori" 3-D microburst data
              models (contextual models). This matching
              process can be performed with one of many
10   techniques used in pattern matching that produces
              a match confidence value. The particular
              technique selected for this application is an
              evidence accrual technique, since all microburst
              features may not necessarily be observable in all
15   cases. Evidence accrual techniques such as the
              Dempster-Schaffer technique can be formulated to
              accrue only available evidence to formulate a
              match confidence (or "degree" of match).
         -    Track position and feature propagation from look
20   to look:
              The position and observed features and spatial
              orientation of observed features are tracked from
              look to look. This is also called temporal
              tracking, since potential microburst position and
25   characteristics are tracked over time. Included
              in this tracking function is spatial location
              association based on airframe motion and scanning
              parameters, feature similarity comparisons to
              alleviate potential mismatches, and the tracking
30   of multiple air masses of interest.
         -    Predicting state of microburst evolution:
              Based on tracked observed air mass features over
              time, a prediction of microburst characteristics
              in the next few minutes of time can be made.
35   This operation is performed on the world
              observation model based on feature tracking over
              time and on known microburst evolution
              information. As an example, it has been observed

that microbursts evolve from converging winds in
the upper atmosphere, followed by a falling high
reflectivity core of air. These features are
observed and tracked by the tracking function.
5   The prediction function predicts a hazardous
divergence in the aircraft's flight path (lower
elevations) if enough evidence of these features
is present in the world observation model.
   -       Wind shear indication:
10   When a region in the world observation model is
of sufficient hazard to the aircraft and is
observed with sufficient confidence level,
cockpit alert indications will be generated.
These indications will have at least two levels
15   advisory and warning. The advisory alert is
given when the wind shear is of no immediate
danger to the aircraft (30 seconds - several
minutes away) and the warning is given if more
immediate danger is present (wind shear 15-30
20   seconds away). As previously stated the
indicators will be both visual and aural cues, as
well as position information on a cockpit radar
display or similar device.
     Simulation display information is provided herein in
25   Figs. 5 and 6 for a simulated "wet" microburst example, and
in Figs 7 and 8 for a simulated "dry" microburst example.
Each display shows one elevation plane of data from the
volumetric scan. The elevation plane shown is the lowest
elevation scanned for these examples, 3 degrees above
30   aircraft glide slope. All displays show azimuth in degrees
along the top of the display, and range in meters along the
right side of the display.
     Fig. 5a represents one elevation plane of data
provided to the reflectivity module 70.
35   Fig. 5b represents one elevation plane of data fed
into the Divergence/Convergence module 50 and the Rotations
module 60. This image divides into two obvious air flow
zones. Area 111 has a positive air velocity (tailwind) and

area 112 has a negative velocity (headwind). Area 115 is
primarily the result of radar sensor "side lobe echo" and
clutter. Areas 113 and 114 are primarily the result of
ground clutter.

5   Fig. 6a represents one elevation plane of the data
output of Divergence/Convergence module 50. Many areas of
interest are shown in Fig 6a.

         The output of Divergence/Convergence module 50 is then
fed into 3-D Spatial Feature Association and Filtering

10   module 90 and the output of module 90 produces the display
of Fig. 6b. It can be seen that the many areas of interest
of Fig. 6a are filtered down to two main areas of interest
in Fig 6b. The darker area is a zone of negative shear
value and the larger lighter gray area is a large zone of

15   positive shear value.

         Fig. 7a represents one elevation plane of raw radar
reflectivity data for a simulated "dry" microburst which is
fed into reflectivity module 70.

         Fig. 7b represents one elevation plane of raw radar

20   velocity data for a simulated "dry" microburst that is fed
into Divergence/Convergence Processor 50 and Rotations
Processor 60. These are mostly blobs of negative velocity
which turn out to be mostly ground clutter. There are a
few small zones of positive velocity.

25   Fig. 8a represents the data output of
Divergence/Convergence module 50.

         The output of Divergence/Convergence module 50 is then
fed into 3-D Spatial Feature Association and Filtering
module 90 and the output of module 90 produces the display

30   of Fig. 8b. In the "dry" case, all but one of the areas of
interest from the Divergence/Convergence module 50 output
were filtered out.

         The one remaining blob 118 in Fig. 8b is the "dry"
microburst, as corroborated by data at higher elevations

35   scans. The rest of the areas of interest of 8a were
clutter. While the blob in Fig. 8b may seem small, it
represents a mass of air on the planes flight path that is
approximately 100 meters across, 150 meters long and 200

meters high and is at a distance of 3.9 KM in front of the
plane.

Now that the construction and operation of the present
invention have been set forth, certain advantages can be
set forth and appreciated. Another approach to airborne
wind shear detection is to use high resolution spectral
editing. In this approach the system attempts to identify
clutter by looking at the Doppler spectrum of the clutter.
The high resolution spectral editing approach requires a
much more sophisticated radar set with its attendant high
cost. The present invention takes the approach of
recognizing the microburst features and then editing the
clutter based on the recognized features. The present
invention can be implemented with less sophisticated and
lower cost radar hardware than the Doppler spectrum
approach. In addition, because of the availability of
upper atmospheric data provided by the volumetric scan 30
of the present invention, there is more information on
which to predict a hazardous wind shear condition. The
additional information available with the present invention
will result in a system that will have a higher detection
probability and fewer alarms. Further, with regard to
detection performance, microbursts can be recognized with
the present invention in there very early stages and well
in advance of the aircraft.

In accordance with the foregoing description,
Applicants have developed an airborne wind shear detection
system that builds on conventional airborne Doppler weather
radar systems. Although a specific embodiment of
Applicants' invention is shown and described for
illustration purposes, a number of variations and
modifications will be apparent to those of ordinary skill
in the relevant arts. It is not intended that coverage be
limited to the disclosed embodiment, but only by the terms
of the following claims.

<u>CLAIMS</u>

1. A wind shear detection system comprising:

antenna means (27) for mounting on an aircraft;

antenna driver means (25), connected to said antenna
means, for driving said antenna means to scan in elevation
and azimuth along the aircraft flight path;

transceiver means (28), connected to said antenna
means, for generating a transmitted signal and for
receiving reflected data;

base data processor means (32), connected to said
transceiver means, for processing the reflected data and
providing atmospheric measurement data for individual
resolution cells that can be formed into a 3-D grid of
atmospheric data samples;

base data filter means (34), connected to said base
data processor means, for removing receiver noise from said
atmospheric measurement data and providing filtered
atmospheric measurement data;

volumetric feature extraction means (40) connected to
said base data filter means, for identifying a plurality of
features within the 3-D grid of the filtered atmospheric
measurement data and grouping said atmospheric data samples
having a first feature into first air masses of interest
and grouping said atmospheric data samples having a second
feature into second air masses of interest;

spatial feature association and filtering means (90),
connected to said volumetric feature extraction means, for
combining said first air masses of interest with said
second air masses of interest to provide a 3-D
representation of atmospheric conditions; and

contextual matching means (100) for comparing said 3-D
representation of atmospheric conditions to a known wind
shear atmospheric conditions model and providing an output
signal when a wind shear threshold condition is exceeded.

2. A windshear detection system comprising:

an airborne scanning doppler radar transceiver (28)
having a three dimensional volumetric scanning pattern
providing measurements that can be formed into a three

dimensional grid of atmospheric data samples (30) with each
data sample (35) having a mean radial velocity and being
characterized by a range, azimuth and elevation;

   means for identifying (52) first radial line segments
wherein consecutive data samples within said first radial
line segments have mean velocity differentials in a first
direction;

   means for comparing (54) each said first radial line
segment to any said first radial line segment located in a
similar position on a radial above each said first radial
line segment to form first 2-D air masses having mean
velocity differentials in a first direction;

   means for comparing 56 each said first 2-D air mass to
any said first 2-D air masses located adjacent to each said
first 2-D air mass to form first 3-D air masses having mean
velocity differentials in a first direction and
representing potential diverging wind conditions;

   means for identifying (52) second radial line segments
wherein consecutive data samples within said second radial
line segments have mean velocity differentials in a second
direction;

   means for comparing (54) each said second radial line
segment to any said second radial line segment located in a
similar position on a radial above each said second radial
line segment to form second 2-D air masses having mean
velocity differentials in a second direction; and

   means for comparing 56 each said second 2-D air mass
to any said second 2-D air masses located adjacent to each
said second 2-D air mass to form second 3-D air masses
having mean velocity differentials in a second direction
and representing potential converging wind conditions.

3.   Windshear detection system of claim 2 further
comprising:

   means for spatially associating (90) said first 3-D
air masses and said second 3-D air masses to provide a
single full volumetric scan spatial representation; and

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means for filtering noise and clutter (90) from said
single full volumetric scan spatial representation to
reveal diverging wind condition locations and converging
wind condition locations.

5

4.   Windshear detection system of claim 3 wherein said
means for filtering comprises means for establishing
knowledge of potential ground clutter regions within said
three dimensional grid and removing 3-D air masses located

10   within said potential ground clutter regions which are not
corroborated by atmospheric data sample measurements at
higher elevations that are known not to include ground
clutter.

15   5.   Windshear detection system of claim 3 wherein said
airborne scanning doppler radar has an antenna (27) mounted
to an airframe and said means for establishing knowledge of
potential ground clutter regions comprises means for
relating parameters from said volumetric scan pattern to

20   information on the attitude of said airframe, position of
said antenna relative to said airframe and beam width of
said antenna.

6.   Windshear detection system of claim 5 wherein said

25   means for filtering further comprises:
means for storing first data models (101) of known
relationships of diverging wind condition locations and
converging wind condition locations in a microburst; and
·means for comparing (100) said single volumetric scan

30   spatial representation to said first stored data models to
determine contextual matching.

7.   Windshear detection system of claim 6 further
comprising means for providing an alerting signal when said

35   diverging wind condition locations and said converging wind
condition locations exceed a predetermined contextual
matching threshold when compared to said stored data
models.

8. Windshear detection system of claim 6 wherein said
first stored data models (101) include a time history
evolution of spatial relationships between diverging wind
5   condition locations and converging wind condition locations
which are known to exist for microburst and windshear
conditions and said windshear detection system further
comprises:
         means for tracking (100) said diverging wind condition
10 locations and said converging wind condition locations over
multiple volumetric scans occurring over a first period of
time; and
         means for comparing (100) said volumetric scans to
said stored first data models which include a time history
15 evolution to permit prediction of where a windshear
condition may occur within a second period of time.

9.   Windshear detection system of claim 6 further
comprising:
20   means for identifying third radial line segments
wherein consecutive data samples within said third radial
line segments have similar reflectivities;
         means for comparing (74) each said third radial line
segment to any said third radial line segment located in a
25 similar position on a radial above each said third radial
line segment to form third 2-D air masses having similar
reflectivities; and
         means for comparing (76) each said third 2-D air mass
to any said third 2-D air masses located adjacent to each
30 said fourth 2-D air mass to form third 3-D air masses
having similar reflectivities.

10. Windshear detection system of claim 9 further
comprising:
35   means for identifying (82) fourth radial line segments
wherein consecutive data samples within said fourth radial
line segments have similar spectral widths;

means for comparing (84) each said fourth radial line
segment to any said fourth radial line segment located in a
similar position on a radial above each said fourth radial
line segment to form fourth 2-D air masses having similar
5   spectral widths; and
means for comparing (86) each said fourth 2-D air mass
to any said fourth 2-D air masses located adjacent to each
said fourth 2-D air mass to form fourth 3-D air masses
having similar spectral widths.
10

11. Windshear detection system of claim 10 further
comprising:
means for merging (90) reflectivity values for said
third 3-D air masses and spectral width values for said
15   fourth 3-D air masses with said diverging wind condition
locations and said converging wind condition locations;
means for storing third data models (101) of known
relationships of diverging wind condition locations,
converging wind condition locations, reflectivity values
20   and spectral width values in a microburst; and
means for comparing (100) said single volumetric scan
spatial representation to said stored third data models to
determine contextual matching (100).

25   12. Windshear detection system of claim 11 wherein said
stored data models include a time history evolution of
spatial relationships between diverging wind condition
locations, converging wind condition locations,
reflectivity values and spectral width values which are
30   known to exist in microburst and windshear condition and
said windshear detection systems further comprises:
means for tracking (100) said locations of said 3-D
air masses having similar reflectivities and said 3-D air
masses having similar spectral widths over multiple
35   volumetric scans occurring over a third period of time; and
means for comparing (100) said volumetric scans to
said stored second data models which include a time history

evolution to permit prediction of where a windshear
condition may occur within a fourth period of time.

13. Windshear detection system of claim 2 further
comprising:
    means for identifying (62) cross azimuth arc segments
having similar velocity differentials between consecutive
range bins on said cross azimuth arc segments;
    means for comparing (64) each said cross azimuth arc
segment to any said cross azimuth arc segment at a similar
azimuth angle and a similar elevation to form fifth 2-D air
masses having similar rates of changing velocity in a cross
azimuth direction;
    means for comparing (66) each said third 2-D air mass
to any said third 2-D air mass located on an elevation
plane above each said third 2-D air mass to form fifth 3-D
air masses having similar rates of changing velocity in a
cross azimuth direction; and
    means for removing noise and clutter influences form
said fifth 3-D air masses to reveal the location of
rotating wind conditions.

14. Windshear detection system of claim 13 wherein:
    means for spatially associating (90) said first 3-D
air masses said second 3-D air masses and said fifth 3-D
air masses to provide a single full volumetric scan spatial
representation; and
    means for filtering (90) noise and clutter form said
single full volumetric scan spatial representation to
reveal diverging wind condition locations, converging wind
condition, locations, and rotating wind condition
locations.

15. Windshear detection system of claim 14 wherein said
means for filtering comprises means for establishing
knowledge of potential ground clutter regions within said
three dimensional grid and removing 3-D air masses located
within said potential ground clutter regions which are not

corroborated by atmospheric data sample measurements at higher elevations that are known no to include ground clutter.

5   16. Windshear detection system of claim 15 wherein said airborne scanning doppler radar has an antenna (27) mounted to an airframe and said means for establishing knowledge of potential ground clutter regions comprises means for relating parameters from said volumetric scan pattern to
10   information on the attitude of said airframe, position of said antenna relative to said airframe and beam width of said antenna.

        17. Windshear detection system of claim 16 wherein said
15   first data models (101) include known relationships of rotating wind conditions.

        18. Windshear detection system of claim 17 wherein said time history evolution of spatial relationships includes
20   rotating wind conditions and said means for tracking includes means for tracking rotating wind condition locations.

        19. Windshear detection system of claim 18 further
25   comprising:
        means for identifying (72) third radial line segments wherein consecutive data samples within said third radial line segments have similar reflectivities;
        means for comparing each said third radial line
30   segment to any said third radial line segment located in a similar position on a radial above each said third radial line segment to form third 2-D air masses having similar reflectivities (74); and
        means for comparing each said third 2-D air mass to
35   any said third 2-D air masses located adjacent to each said third 2-D air mass to form fourth 3-D air masses having similar reflectivities.

20. Windshear detection system of claim 19 further
comprising:

        means for identifying (82) fourth radial line segments
wherein consecutive data samples within said fourth radial
5   line segments have similar spectral widths;

        means for comparing each said fourth radial line
segment to any said fourth radial line segment located in a
similar position on a radial above each said fourth radial
line segment to form fourth 2-D ear masses having similar
10   spectral widths; and

        means for comparing (86) each said fourth 2-D air mass
to any said fourth 2-D air masses located adjacent to each
said fourth 2-D air mass to form fourth 3-D air masses
having similar spectral widths.

15

21. Windshear detection system of claim 20 further
comprising:

        means for merging (90) reflectivity values for said
third 3-D air masses and spectral width values for said
20   fourth 3-D air masses with said diverging wind condition
locations, converging wind condition locations; and said
rotating wind condition locations;

        means for storing fourth data models (101) of known
relationships of diverging wind condition locations,
25   converging wind condition locations, rotating wind
condition locations, reflectivity values and spectral width
values in a microburst; and

        means for comparing (100) said single volumetric scan
spatial representation to said stored fourth data models to
30   determine contextual matching.

22. A windshear detection system comprising:

        and airborne scanning doppler radar transceiver having
a three dimensional volumetric scanning pattern (30)
35   providing measurements that can be formed into a three
dimensional grid of atmospheric data samples (35) with each
data sample having a mean velocity and being identified by
a coordinate location;

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means for identifying (52) first radial line segments wherein consecutive data samples within said first radial line segments exhibit a feature selected from among a plurality of predetermined features;

5   means for comparing (54) each said first radial line segment to any said first radial line segment located in a similar radial position on a radial above each said first radial line segment to form a 2-D air mass having said selected feature;

10   means for comparing (56) each said 2-D air mass to any said 2-D air mass located adjacent to each said 2-D air mass to form 3-D air masses having said selected feature, said 3-D air masses representing potential locations of an atmospheric indictor useful in predicting a windshear

15   condition.

23. Windshear detection system of claim 22 wherein said selected feature is a velocity differential in a first direction.

20

24. Windshear detection system of claim 23 wherein said selected feature is a velocity differential in a second direction.

25   25. Windshear detection system of claim 24 wherein said selected feature is similar reflectivity.

26. Winds hear detection system of claim 25 wherein said selected feature is similar spectral width.

FIG.1

2/10
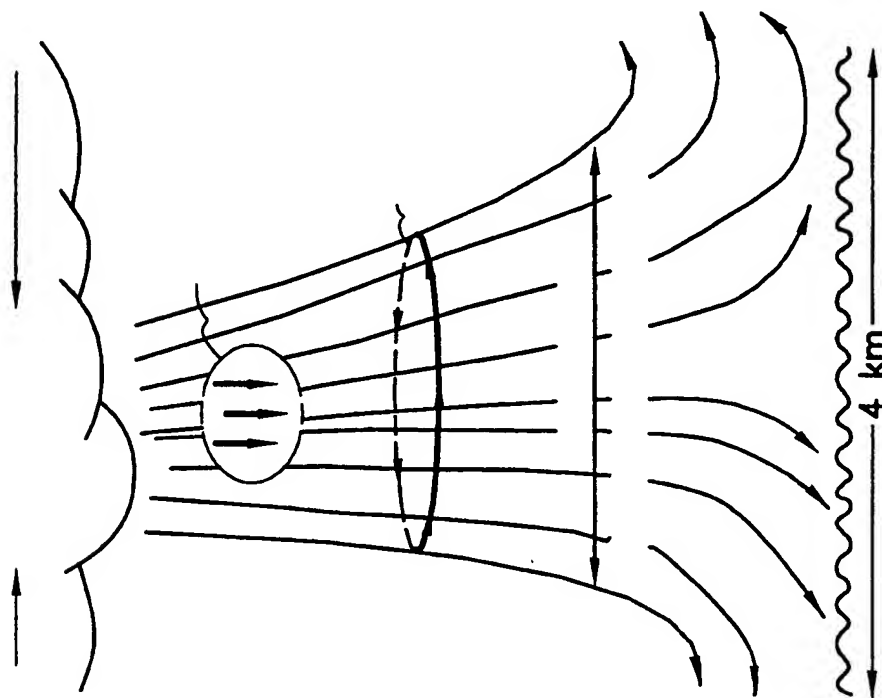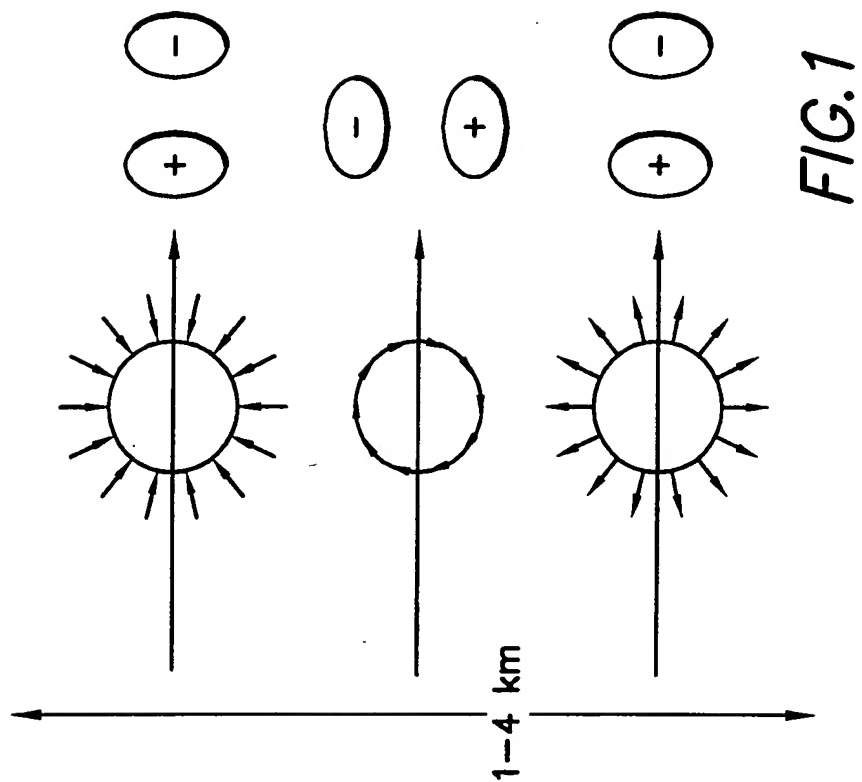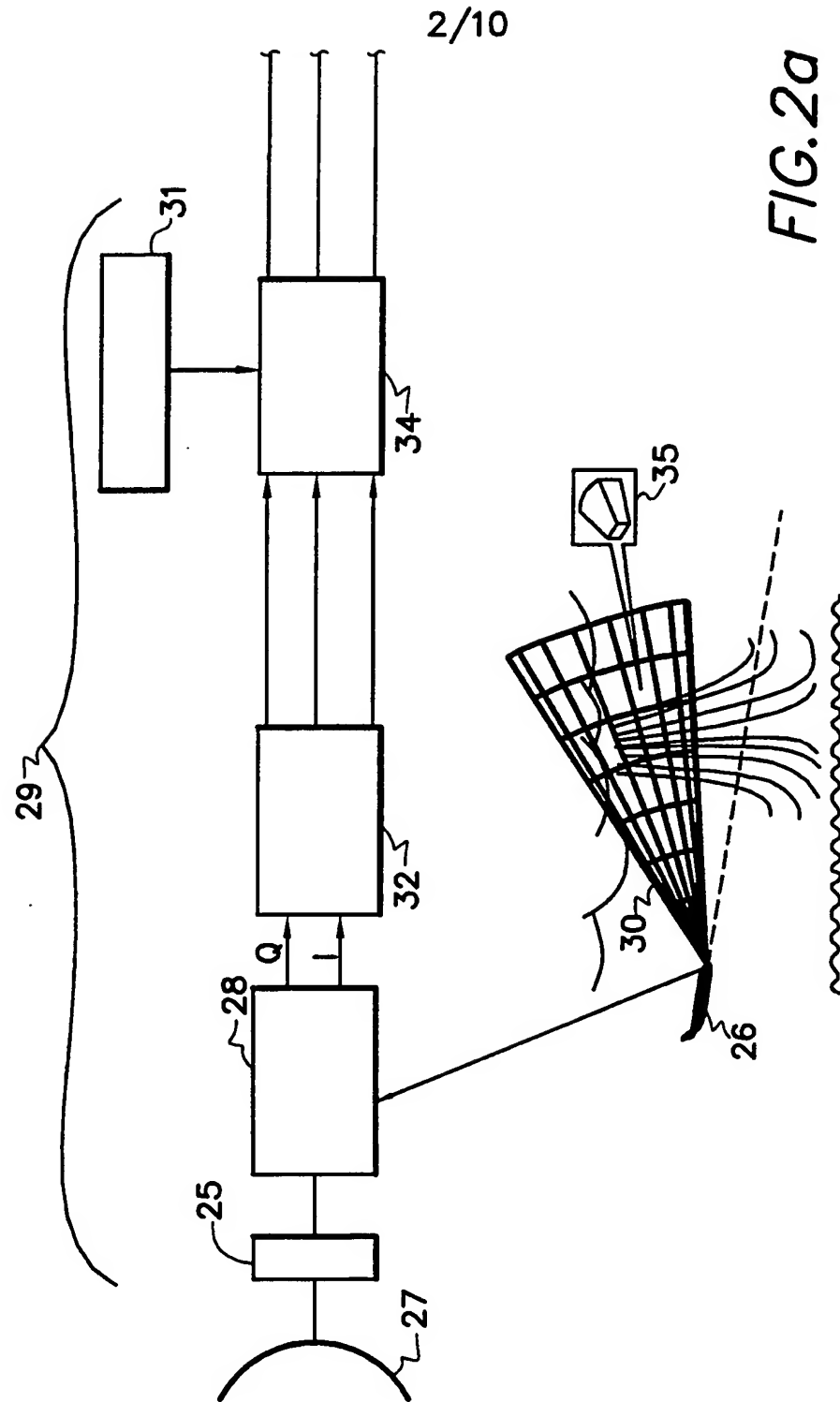
FIG.2a
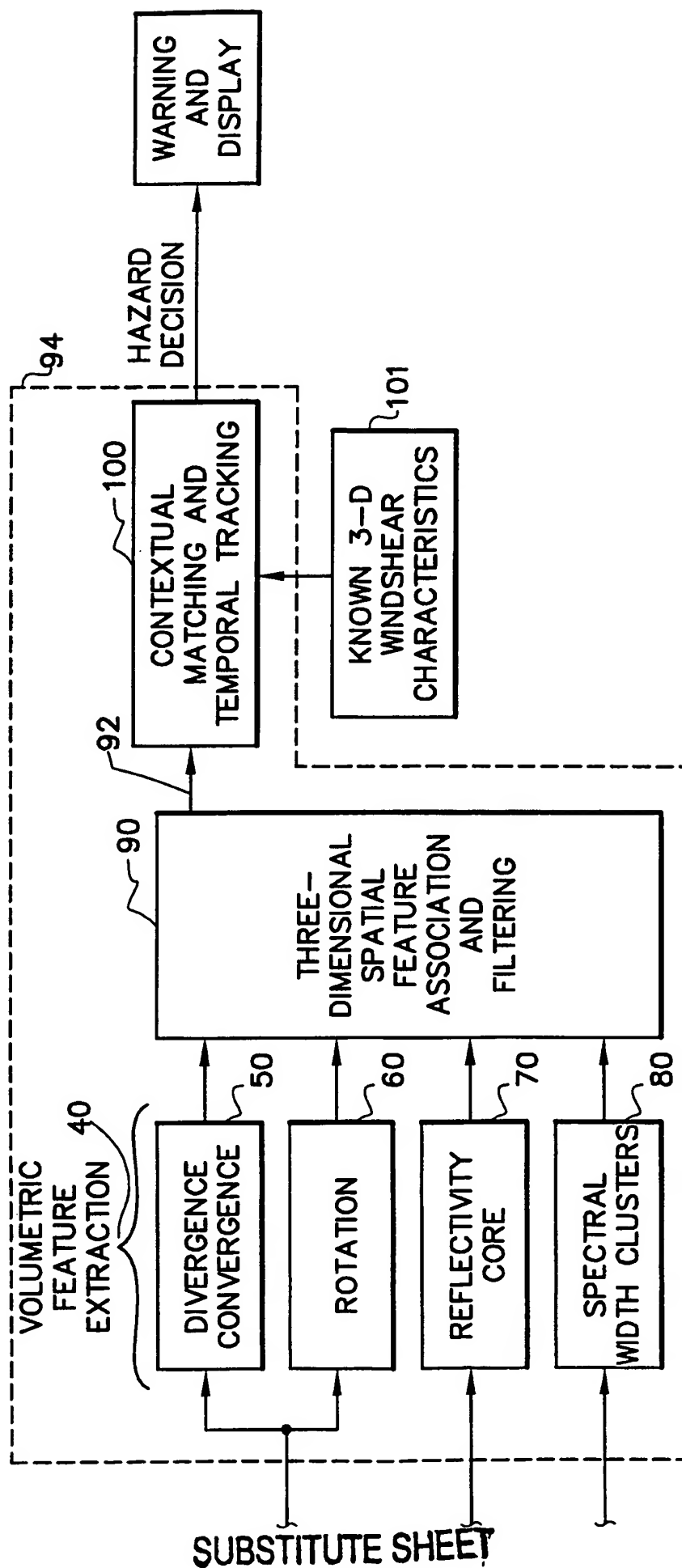
FIG.2b
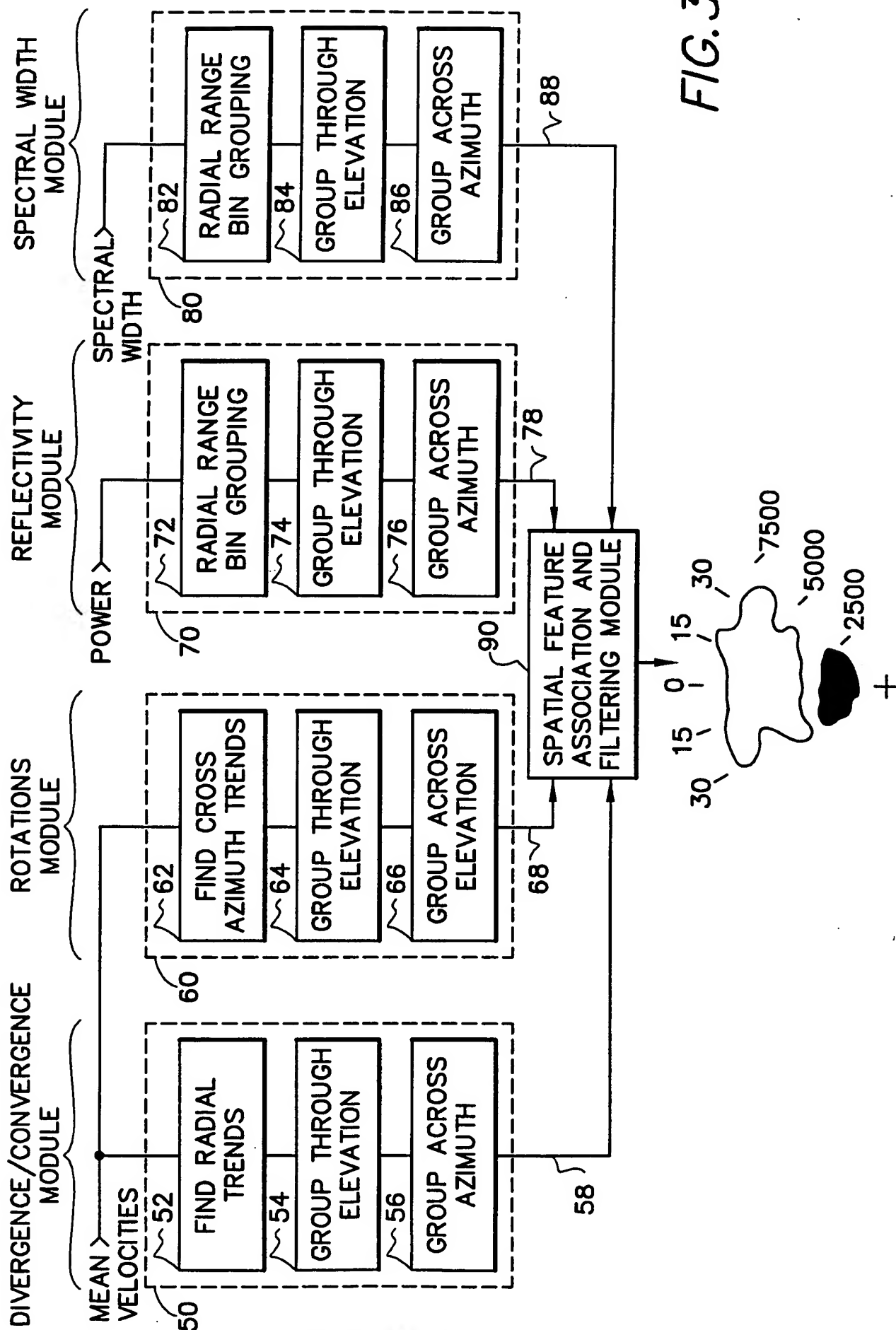
FIG.3

FIG. 4a
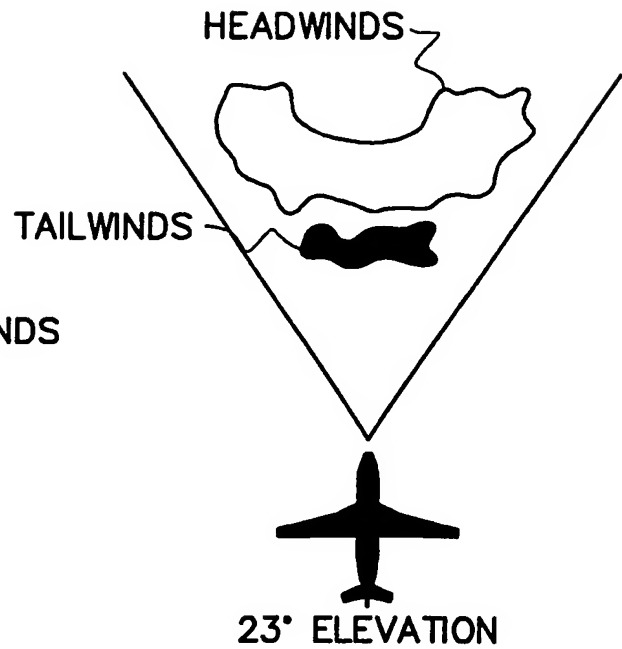
FIG. 4b
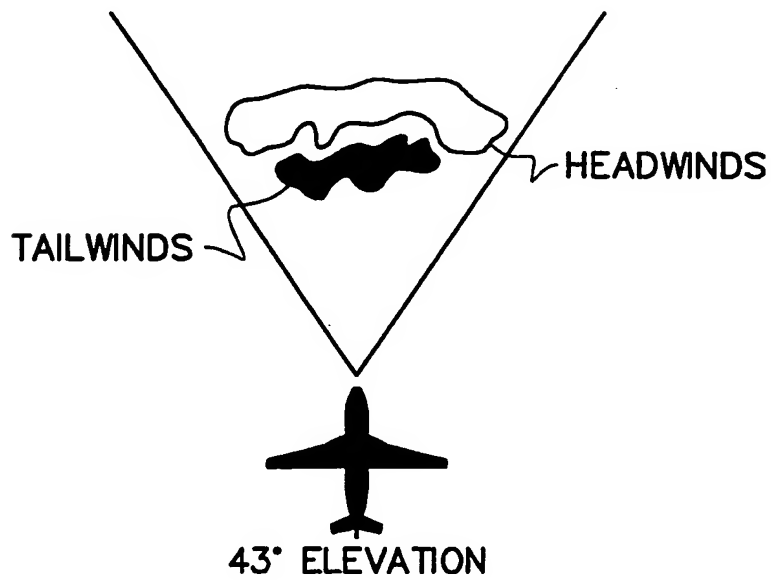
FIG. 4c

FIG.5a

FIG.5c

FIG.5b
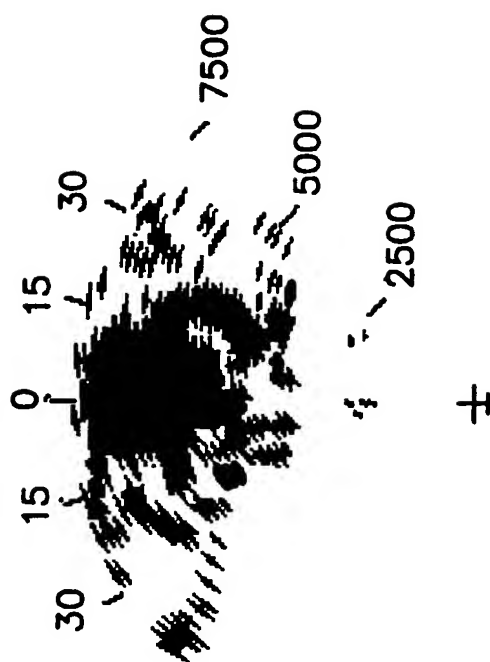
FIG.6b

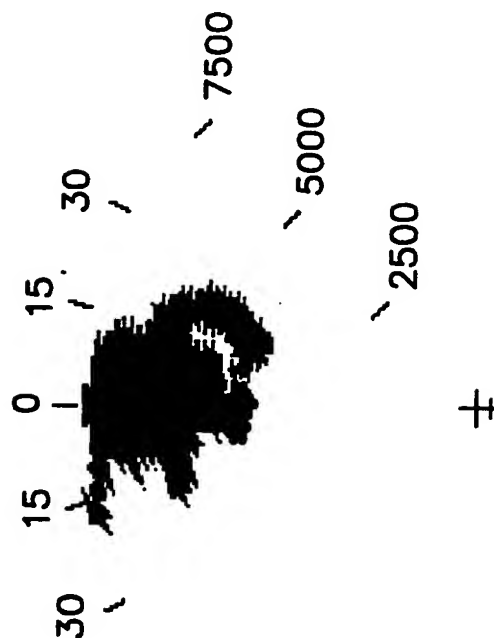FIG.6a

FIG.7b

FIG.7a

FIG.8b

FIG.8a

INTERNATIONAL SEARCH REPORT
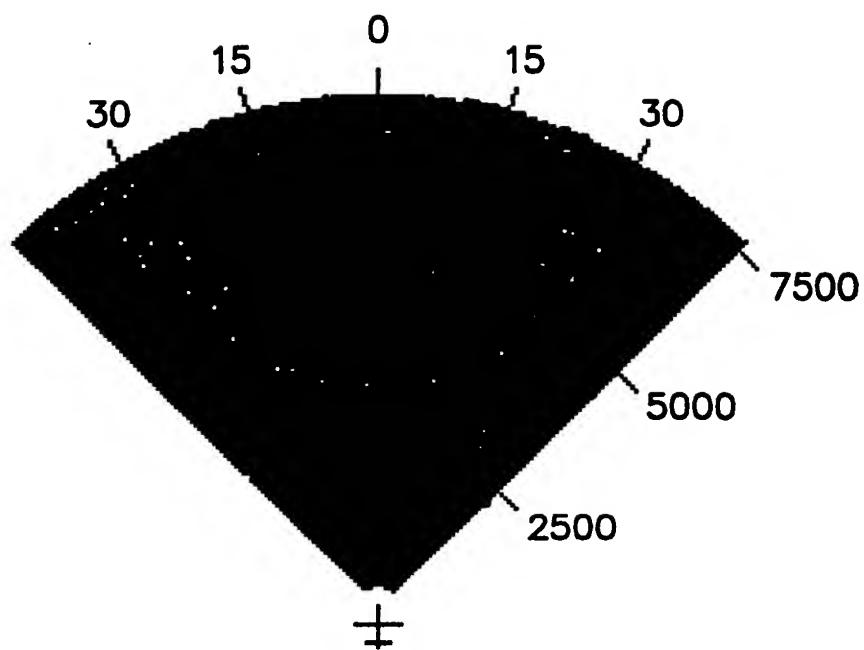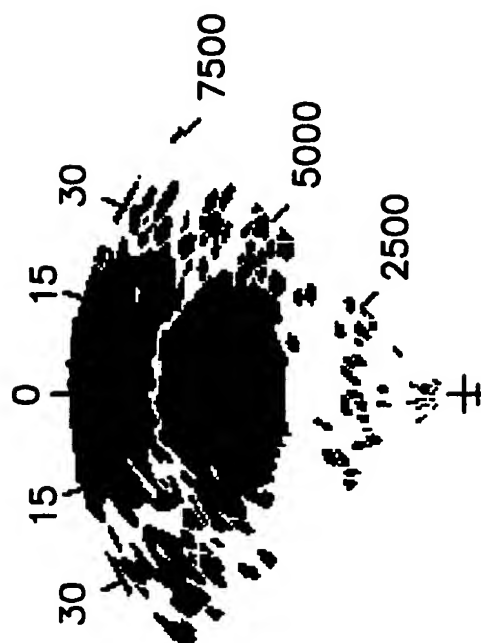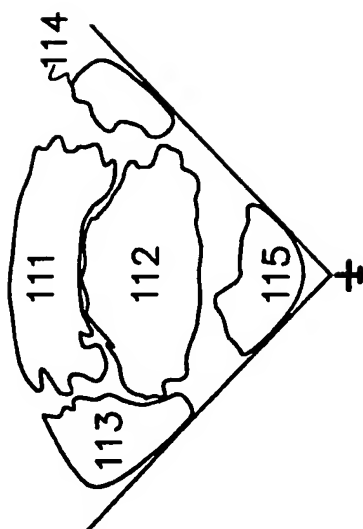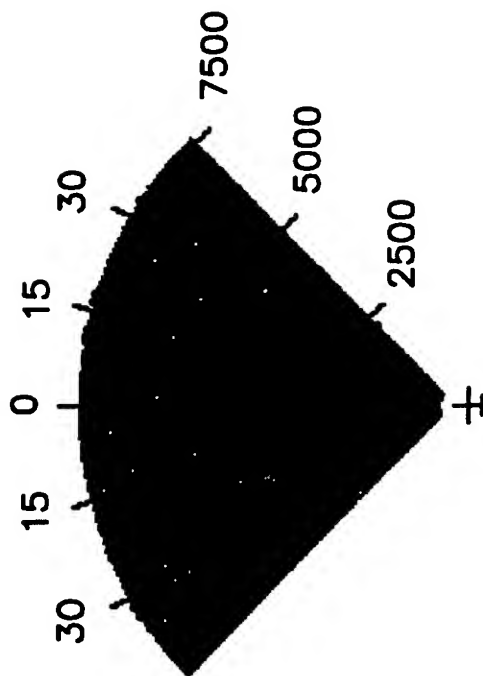
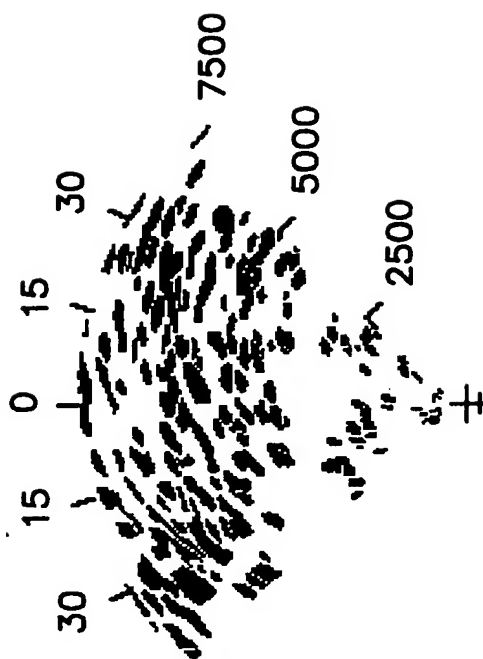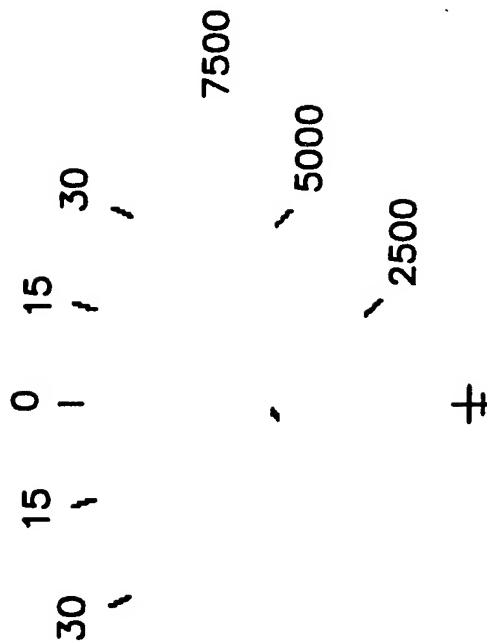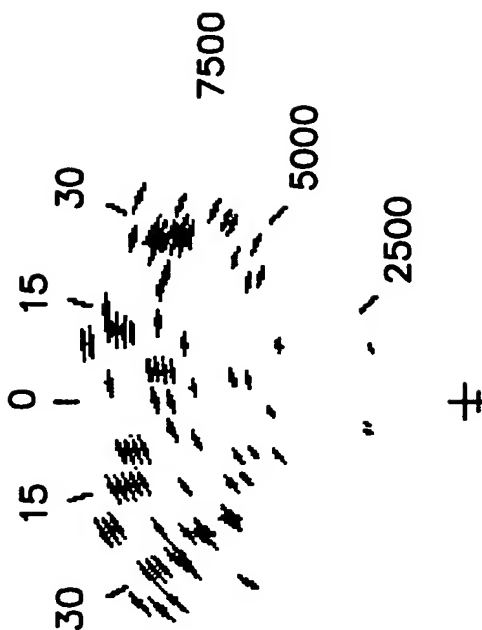## A. CLASSIFICATION OF SUBJECT MATTER
IPC 5   G01S13/95

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 5   G01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US,A,5 202 690 (FREDERICK) 13 April 1993 see abstract; figures 1,3 see column 3, line 44 - column 6, line 19 ---	1,2,22
A	US,A,5 198 819 (SUSNJARA) 30 March 1993 see column 6, line 24 - column 7, line 30; figures 1,2 ---	1,2,22
A	US,A,5 130 712 (RUBIN ET AL.) 14 July 1992 see column 10, line 36 - column 11, line 50 --- -/--	1,2,6, 22-26

[X] Further documents are listed in the continuation of box C.   [X] Patent family members are listed in annex.

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
2 December 1993	2 0. 01. 94

Name and mailing address of the ISA European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+ 31-70) 340-2040, Tx. 31 651 epo nl, Fax (+ 31-70) 340-3016	Authorized officer Zaccà, F

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	IEEE TRANSACTIONS ON GEOSCIENCE ELECTRONICS vol. GE-17, no. 4 , October 1979 , NEW YORK US pages 250 - 262 CRANE 'Automatic Cell Detection and Tracking' see paragraph II.A -paragraph III.A -----	1,2,22

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US-A-5198819	30-03-93	NONE		
US-A-5130712	14-07-92	AU-A-	1673792	17-11-92
		WO-A-	9218877	29-10-92
		US-A-	5262782	16-11-93